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MARS RECONNAISSANCE ORBITER MANEUVER PLAN FOR MARS 2020 ENTRY, DESCENT, AND LANDING SUPPORT AND BEYOND

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The Mars Reconnaissance Orbiter (MRO) spacecraft continues to perform valuable science observations at Mars, provide telecommunication relay for surface assets, and characterize landing sites for future missions. MRO provided primary relay support for the InSight Mission during Entry, Descent, and Landing (EDL) on November 26, 2018. This paper discusses the current maneuver plan to support Mars 2020 EDL and maintain MRO's orbit for science operations through 2028.

INTRODUCTION

The Mars Reconnaissance Orbiter (MRO) spacecraft is currently in its fourth extended mission at Mars. The Primary Science Orbit (PSO) for MRO operations is a 252 km $\times$ 317 km altitude, sun-synchronous orbit with the periapsis frozen over the south pole and the ascending node at 3:00 PM Local Mean Solar Time (LMST). In addition to making science observations at Mars, MRO is expected to continue providing relay support for surface assets. For telecommunication and imaging support during the InSight Mission's Entry, Descent and Landing (EDL) sequence on November 26, 2018, MRO had moved its orbit to around 2:52 PM LMST.[1] To support Mars 2020 for its scheduled landing on February 18, 2021, MRO has been requested to transition to a 3:15 PM LMST by the time of EDL. MRO may also support the ExoMars 2020 Mission which is planned to land on Mars shortly thereafter. This paper will discuss the current maneuver plan to satisfy Mars 2020 EDL support requirements.

MRO nominally implements a propulsive Orbit Trim Maneuver (OTM) to either maintain the PSO orbit or position the orbiter for relay support for such events as InSight EDL. After a battery anomaly occurred on September 13, 2017 following the execution of OTM-49, minimizing the Sun eclipse durations experienced by the spacecraft was identified as one possible action to improve battery capacity. This led to the maneuver plan to move MRO to a 4:30 PM LMST following Mars 2020 EDL support to reduce the eclipse durations.[2] However, the current battery charging strategy employed by MRO has yielded encouraging results rendering this plan unnecessary. The proposed maneuver plan following Mars 2020 EDL is now to maintain MRO's orbit LMST near 3:15 PM which is at the upper bound of the PSO requirement (3 PM $\pm$ 15 minutes).[3] This manuscript will also describe this maneuver strategy to maintain MRO's orbit for science operations through 2028.

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MISSION OVERVIEW

MRO was launched from Cape Canaveral Air Force Station on August 12, 2005. After an interplanetary cruise of seven months, it reached Mars on March 12, 2006. Following the Mars Orbit Insertion (MOI) and a period of aerobraking, MRO completed the Primary Science Phase (PSP), Extended Science Phase (ESP), and subsequently, three extended missions (EM1, EM2, and EM3). MRO is currently in its fourth extended mission (EM4) which ends in 2019. The MRO Navigation Team has been providing mission support through these mission phases by performing the spacecraft orbit determination (OD) and maintaining the PSO through propulsive maneuvers.

MRO Spacecraft

The spacecraft axes, as shown in Figure 1, are defined such that +Z is positive along the nadir deck where the majority of the science instruments are located. The six engines for MOI and the six Trajectory Correction Maneuver (TCM) thrusters are located along the +Y axis. The large solar panels are on the ±X axes, canted 15 deg towards +Z. The 3-meter diameter High Gain Antenna (HGA) is located opposite the nadir deck. During science operations, the nadir deck is configured towards Mars, while the X-axis is directed along the velocity vector. Both the panels and HGA will swivel to track the Sun and Earth, respectively. MRO is gravity-gradient stabilized to sustain the nadir-to-planet orientation. Spacecraft attitude is maintained by the Reaction Wheel Assembly (RWA); this consists of three 100 Nms wheels mounted perpendicular to each other, augmented by a fourth redundant wheel in a skewed orientation.[4] The monopropellant propulsion subsystem uses three sets of thrusters; these include the MOI, TCM, and Attitude Control System (ACS) thrusters. The TCM thrusters have been used for OTMs since February 2007. Note that the ACS system is coupled; thruster pairs are fired such that it nominally imparts a net zero ΔV (i.e., balanced thrusters).[4] The spacecraft bus built by Lockheed Martin provides a stable platform for the payload suite of science instruments. These instruments, mounted for observation on the +Z axis of the spacecraft (nadir deck), are used to perform remote sensing of the Martian atmosphere as well as surface and subsurface conditions. Among MRO's instruments, high fidelity imagery is performed using the High Resolution Imaging Science Experiment (HiRISE) camera. This key resource is able to supply imaging of orbiting or landed assets on Mars as well as mission support observations of possible future landing site locations. Relay telecommunication support in the UHF frequency range is provided by the Electra Proximity Link Payload.

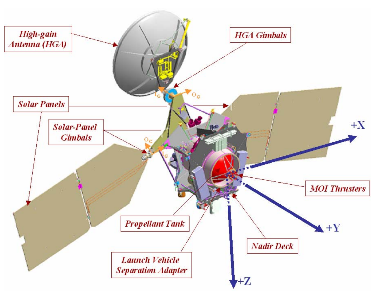


Figure 1: MRO Spacecraft

MRO Primary Science Orbit

The MRO PSO is defined by the following three characteristics, designed to satisfy science and mission requirements by maintaining an orbit which optimizes the science instrument performance:

- Near-repeat ground track walk (GTW) in every 17-day, 211-orbit (short-term repeat) MRO targeting cycle; exact repeat is after 4602 orbits. The nominal GTW is 32.45811 km West in each 211-orbit cycle.
- Periapsis is frozen about the Mars South Pole. The mean eccentricity vs. mean argument of periapsis ($e - \omega$) space is used to track this frozen orbit condition.

- Sun-synchronous orbit ascending node at 3:00 PM $\pm$ 15 minutes LMST at the daylight equatorial crossing.

OVERVIEW OF MANEUVER SUPPORT

MRO Navigation has performed OTMs in typically one of two standard maneuver orientations, or a hybrid of the two: in-plane (parallel to the spacecraft velocity vector) or out-of-plane (along the spacecraft angular momentum vector). The burns are executed as fixed-attitude maneuvers and are usually scheduled for the first Wednesday morning of a new two-week spacecraft background sequence starting on Sunday. For the MRO maneuver history and performance since March 2017, see Appendix A.

In-Plane Maneuvers

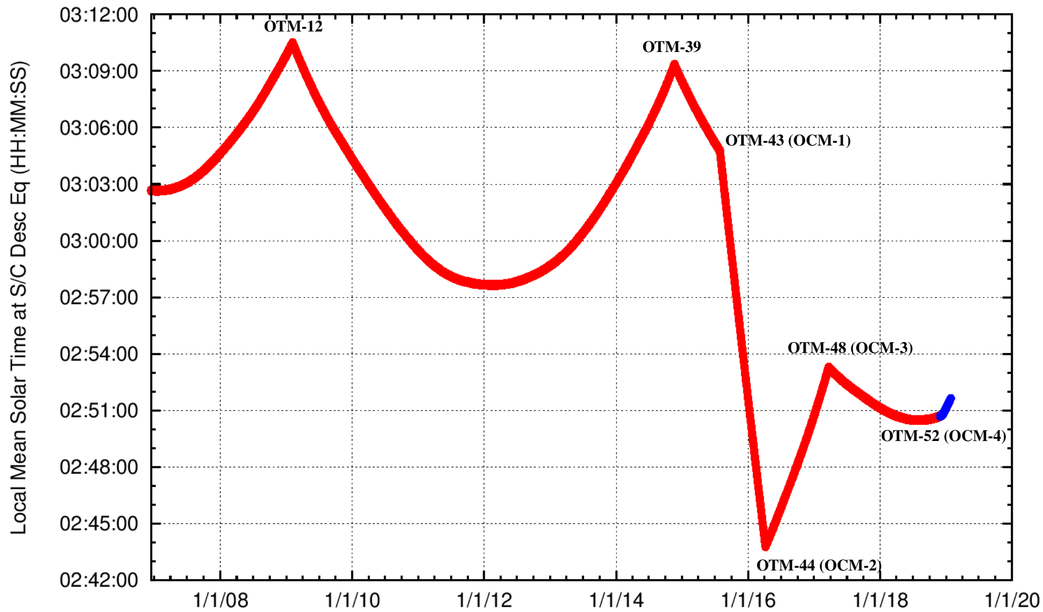
Maneuvers performed along the spaecraft velocity vector are used to control GTW error and to phase MRO for support of incoming spacecraft such as the InSight lander.

GTW Maintenance Maneuvers The nominal GTW to be achieved by MRO is 32.45811 km West each near-repeat 211-orbit cycle. Atmospheric drag reduces the energy of MRO in its orbit, which in turn decreases the orbital period and increases the GTW error. To counter drag, MRO nominally performs in-plane OTMs in the pro-velocity direction at one of the orbit apses to increase the orbital period and slow the GTW. The choice to execute at periapsis or apoapsis usually depends on two factors: the OTM placement allows sufficient tracking before and after the maneuver, and the frozen orbit condition is adequately controlled (e-ω space at periapsis). In Appendix B, Figure 7 shows the maintenance of the 211-orbit GTW repeat error since January 2017 and Figure 8 presents the entire mean e-ω reconstructed history through OTM-52.

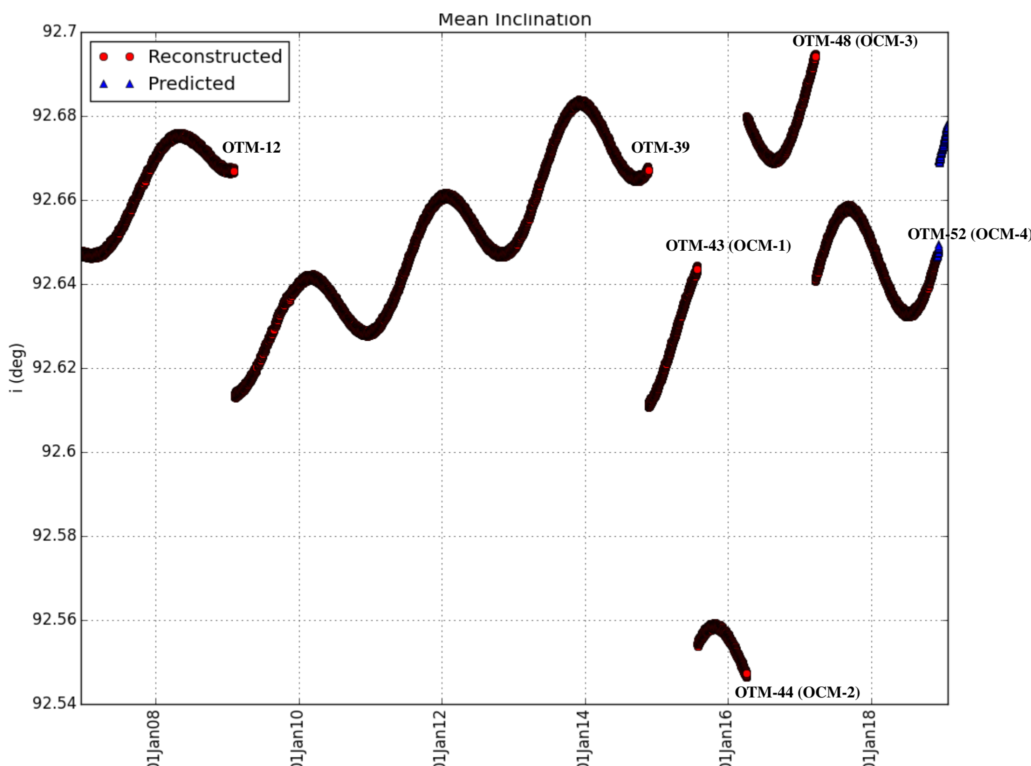
Phasing Maneuvers Orbit phasing is accomplished through in-plane Orbit Synchronization Maneuvers (OSMs). An OSM is used to adjust the MRO orbital period and, over a given duration, produce a desired total MRO orbit down-track timing change. OSMs have been performed in support of the EDL sequences of the following missions: Phoenix lander in May 2008,[5] Mars Science Laboratory (MSL) in August 2012,[6] ExoMars Schiaparelli lander in October 2016,[7] and InSight lander in November 2018.[1] They were also used to move MRO to a protected location from the Comet Siding Spring incoming particles in October 2014.[8]

Out-of-Plane Maneuvers

The MRO orbit LMST is adjusted via small changes in orbit inclination which causes the orbit LMST to drift to the desired control band. An inclination change maneuver is most efficiently performed at an orbit ascending or descending node; the maneuver is applied along the orbit angular momentum vector. The secular nodal rate change, which in turn can be transformed into a LMST rate change, can be controlled via adjusting the orbit inclination. The timing interval between the maneuver epoch and the target epoch determines the LMST rate change needed. The impulsive ΔV to implement a desired inclination change, for an intended nodal rate change, can be accomplished in the burn frame via an out-of-plane ΔV. The maneuver needed to achieve a desired orbit inclination change is simulated as a finite maneuver in operations; the maneuver magnitude is adjusted iteratively through simulation until the desired inclination correction (and intended LMST at some future epoch) is obtained.[6] Figure 2a shows the reconstructed LMST profile from January 2007 through December 2018 (in red) with labels of the inclination-change maneuvers which affected the LMST drift. For the same period, the mean inclination profile is given in Figure 2b.



(a) MRO LMST from Jan. 2007 – Dec. 2018. *Reconstructed (red), predicted (blue).*



(b) Mean Inclination from Jan. 2007 – Dec. 2018. *Reconstructed (red), predicted (blue).*

Figure 2: Reconstructed LMST and Mean Inclination Profiles from January 2007 – December 2018.

Inclination-Change Maneuvers for PSO Maintenance Inclination-change maneuvers are designed such that the PSO requirement for LMST (3:00 PM $\pm$ 15 minutes) is maintained. They have been implemented three times in the mission to drift the LMST back towards 3:00 PM at the ascending equator crossings: OTM-12 in February 2009, OTM-39 in November 2014, and OTM-44 in April 2016. The spacecraft is currently restricted to operate within a Local True Solar Time (LTST) range of 2 PM to 4 PM. Hence, the orbit plane change maneuvers were designed complying with this limitation. Small margin was also provided to ensure this range was not violated.

Inclination-Change Maneuvers for EDL Support Three OCMs have been implemented in relation to InSight EDL support. OTM-43 (OCM-1) was performed on July 29, 2015 at the descending equator crossing to change the nodal drift such that 2:30 PM LMST would be achieved on September 28, 2016, the original date for InSight EDL. Due to OTM-43 execution errors, the expected LMST at the time of InSight EDL was about 2:29:40 PM (20 sec early), well within the LMST requirement (-10 min $\leq$ target LMST $\leq +30$ sec). After the postponement of the InSight launch, OTM-44 (OCM-2) on April 6, 2016 was performed at the ascending equator crossing to re-establish the 3:00 PM LMST PSO configuration. OTM-48 (OCM-3) was performed on March 22, 2017 with a ΔV size of about 3.2 m/s to arrest the LMST drift such that the 2:52 PM LMST requirement was met by the InSight EDL timeframe on November 26, 2018. Due to execution errors from OTM-48, the LMST at the time of InSight EDL was predicted to be $\sim$2:50:40 PM, approximately a minute early from the requested LMST but again within the requirement. For Mars 2020 EDL support, OTM-52 (OCM-4) was performed successfully on December 12, 2018 to meet the 3:15 PM LMST requirement. This maneuver will be described in a later section.

Combined Maneuvers

In-plane and out-of-plane maneuvers for orbit phasing and LMST control, respectively, may be performed independently. However, both in-plane and out-of-plane components may be combined into a single maneuver for operational convenience and to reduce ΔV expenditure. This combined-maneuver approach was implemented in the designs of six OTMs which are given in Table 1. This table also lists the in-plane and out-of-plane components that were used to determine the combined ΔVs. To date this combined-maneuver approach produced a savings of nearly 2.4 m/s.

Table 1: Inclination-Change Maneuver History

Maneuver	Maneuver Epoch (UTC-SCET)	Node	Independent ΔVs		Combined ΔV (m/s)	Ind. ΔVs $-$ Comb. ΔV (m/s)	LMST Target
			ΔV_{Out} (m/s)	ΔV_{In} (m/s)			
OTM-12	04-Feb-2009 17:55:27	DEqX	3.2000	0.0610	3.2006	0.0604	3:00 PM PSO Maintenance
OTM-39	19-Nov-2014 13:21:44	DEqX	3.3000	1.0124	3.4518	0.8606	3:00 PM PSO Maintenance
OTM-43 (OCM-1)	29-Jul-2015 13:21:31	DEqX	5.3300	0.0910	5.3308	0.0902	2:30 PM @ InSight 2016 EDL
OTM-44 (OCM-2)	06-Apr-2016 13:31:09	AEqX	7.9000	0.4760	7.9143	0.4617	3:00 PM PSO Maintenance
OTM-48 (OCM-3)	22-Mar-2017 13:38:40	DEqX	3.1700	0.4120	3.1967	0.3853	2:52 PM @ InSight 2018 EDL
OTM-52 (OCM-4)	12-Dec-2018 14:18:23	DEqX	1.2000	0.7270	1.4030	0.5240	3:15 PM @ Mars 2020 EDL
						2.3822 m/s savings	

All six of these OTMs met the LMST requirements while maintaining the GTW error within prescribed bounds. For example, at the time of OTM-39 the GTW error had nearly reached $+240$ km. Performing a maneuver exclusively to control the GTW error back to -40 km would have cost about 1 m/s, but combining the in-plane component with a 3.3 m/s out-of-plane ΔV for LMST maintenance added only 0.15 m/s to the total ΔV of 3.45 m/s.

Maneuver Scheduling

In May 2011 the GTW control band strategy was relaxed to $\pm$40 km (from $\pm$20 km), allowing maneuvers to be scheduled 8 weeks apart. Since March 2017, the maneuver spacing has been approximately 6 months during low-density seasons. However, during high-density seasons the maneuver frequency remains 8 weeks and maneuvers cancellations are determined on a case-by-case basis. This change was also due to the GTW control band being further relaxed to $\pm$60 km for EM4. Maneuver spacing has also been modified to avoid certain time frames, such as solar conjunction or holiday periods. Placements of the orbit-phasing and inclination-change maneuvers are independent of the GTW maintenance maneuvers locations, but may coincide with the latter's schedule which is based on the expected atmospheric drag ΔVs.

Following the battery anomaly which occurred on September 13, 2017 right after OTM-47, subsequent maneuvers are now preceded by power and thermal subsystems assessments when in the past it was limited to Attitude Control Systems (ACS) analysis. This requires that the maneuver design process and assessment begins earlier for each maneuver. Additionally. the orbit location for each maneuver also needs to be analyzed to ensure it is acceptable for each subsystem.

MRO SUPPORT FOR MARS 2020 EDL

The Mars 2020 spacecraft will be launched in the July–August 2020 timeframe on an Atlas-V 541 launch vehicle from Cape Canaveral Air Force Station (CCAFS) on a Type 1 transfer trajectory to Mars. The current baseline target landing location for Mars 2020 is in the Jezero Crater in the Syrtis Major quadrangle at 18.45° N, 77.46° E.[9] The Mars 2020 EDL sequence is expected to last between six and seven minutes.

The Mars 2020 Mission has requested MRO to move its orbit ascending node to 3:15 PM LMST at the time of Mars 2020 EDL on February 18, 2021 and to be between -5 minutes and $+20$ minutes of this LMST target (i.e., between 3:10 PM to 3:35 PM LMST). This LMST target range is currently being assessed by the Mars 2020 project. Additionally, the Mars 2020 Mission has asked that MRO phases within $\pm$30 seconds of the specified Mars 2020 entry epoch, which corresponds to within $\pm$1.6 degrees of a targeted latitude specified at Mars 2020 entry.

OCM Strategy for Mars 2020 EDL and Beyond

The 20181115 Reference Trajectory provides the tentative plan for supporting Mars 2020 EDL at 3:15 PM LMST and then maintaining MRO's orbit near 3:15 PM LMST.[3] In this reference trajectory, the total required maneuver ΔV is 10.32 m/s, accomplished via OCMs 4–7 (see Table 5). This total ΔV does not include any in-plane maneuver ΔVs needed for ground track walk error control or EDL phasing support. Atmospheric drag was not modeled and burns were centered at the descending equator crossings. The ΔV and estimated propellant usage for each maneuver can be found in Table 5, as well as the inclination change and the LMST at the time of each maneuver. OCMs 1–3 were previously performed for InSight EDL support and are described in Reference 10.

In this reference trajectory, OCM-4 is modeled on December 12, 2018 to change the nodal drift such that 3:15 PM LMST is achieved for Mars 2020 EDL on February 18, 2021. OCM-4 is performed immediately after InSight EDL support which occurred on November 26, 2018 to avoid crossing 2 PM LTST (MRO is currently required to operate between 2 PM and 4 PM LTST). OCM-5 is planned for April 14, 2021 to reverse the nodal drift such that a minimum LMST of $\sim$3:14:30 PM is achieved in June 2022. This OCM is scheduled just after the support of both Mars 2020 EDL in February 2021 and ESA's ExoMars RSP first overflights in March 2021. OCM-6 on March 27, 2024 again arrests the LMST drift and maintains the PSO by achieving a minimum LMST of $\sim$3:14 PM in February 2026. Finally, OCM-7 on December 15, 2027 maintains the PSO by achieving a minimum LMST of $\sim$3:14 PM in November 2029. Note that the OCM dates, orbital locations, and ΔVs are reference values that are subject to change. Also, OCMs 5–7 were designed such that the LMST varies by only up to 5 minutes from 3:15 PM and the LTST remains between the operational limits of 2 PM and 4 PM.

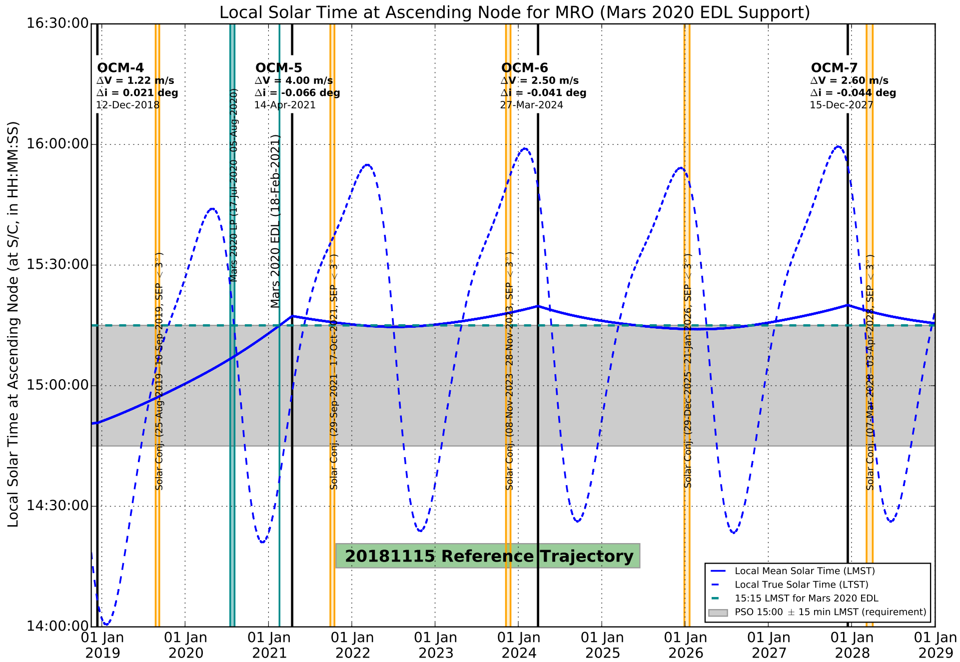
Table 2: OCM Strategy for Mars 2020 EDL at 3:15 PM LMST and MRO Science Operations Near 3:15 PM LMST Through 2028

Maneuver	Maneuver Epoch (UTC-SCET)	ΔV (m/s)	Prop. Usage (kg)	Inc. Change (deg)	LMST at Time of OCM	Comments
OCM-4	12-Dec-2018 14:19:49	1.22	0.66	0.021	2:50:46 PM	Achieve 3:15 PM LMST for Mars 2020 EDL
OCM-5	14-Apr-2021 13:26:58	4.00	2.17	−0.066	3:17:24 PM	Maintain near 3:15 PM LMST through Mar. 2024
OCM-6	27-Mar-2024 13:50:35	2.50	1.36	−0.041	3:19:46 PM	Maintain near 3:15 PM LMST through Dec. 2027
OCM-7	15-Dec-2027 13:43:57	2.60	1.41	−0.044	3:20:05 PM	Maintain near 3:15 PM LMST beyond 2028
	Total	**10.32**	**5.60**			

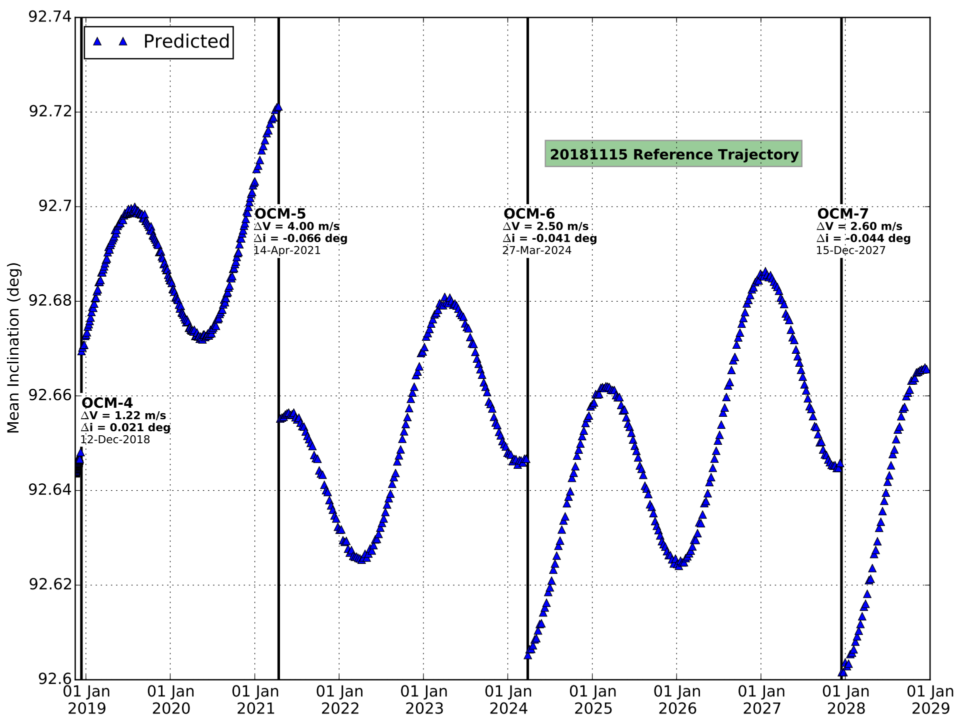
Figure 3a displays the local solar time profile (LMST and LTST) from November 15, 2018 through January 1, 2029. OCMs 4–7 are indicated in the plot, as well as the Mars 2020 launch and EDL support periods. The solar conjunction periods are also highlighted. The minimum LTST following OCM-4 is $\sim$2:00:30 PM on January 20, 2019 and the LTST remains between 2 PM and 4 PM through the end of 2018 (MRO is required to operate within this LTST range). Figure 3b shows the mean inclination profile from November 15, 2018 through January 1, 2029.

OCM-4 Performance

OTM-52 (OCM-4) was performed successfully on December 12, 2018 to change the nodal drift such that the 3:15 PM LMST requirement at Mars 2020 EDL will be achieved. The estimated LMST at Mars 2020 EDL following the performance of OTM-52 was $\sim$3:13:20 PM. This difference from the requested LMST target was primarily due to the $\sim$1.44° right ascension error in the commanded maneuver, a larger pointing error than observed with past maneuvers. The minimum LTST following OTM-52 moved slightly earlier to January 18, 2019 and is currently estimated to be $\sim$2:00:25 PM. OTM-52 was also used to remove a large $\sim$213 km GTW repeat error that had built up since the InSight EDL phasing campaign began (via a 0.727 m/s in-plane component).



(a) Local Solar Time Profile



(b) Mean Inclination Profile

Figure 3: Local Solar Time and Mean Inclination Profiles (20181115 Reference Trajectory)

OSM Strategy for Mars 2020 EDL

The atmospheric density variation is the largest contributor to errors in the MRO navigation accuracy, other than a significant maneuver execution error. Figure 4 shows the atmospheric drag ΔV per orbit experienced by MRO since PSP through each succeeding mission phase, plotted against solar longitude. The solar longitudes of the Phoenix, MSL, Schiaparelli (EDM), and InSight EDLs are labeled, as well as the Comet Siding Spring flyby. This plot has been used to anticipate the drag ΔVs leading to each EDL sequence in order to determine the OSM placements and the associated navigation timing uncertainties.

The phasing opportunities for Mars 2020 begin soon after the close of the launch window in September 2020 and last through early February 2021. The atmospheric drag ΔV per orbit during this time frame corresponds to solar longitudes beginning right at 270° which historically is the peak of the high density season. According to Figure 4, the drag ΔV can range from 0.4 mm/s/orbit as seen in EM4 to above 0.7 mm/s/orbit as seen in EM2 and EM3. Like the InSight EDL phasing window with drag ΔVs ranging from 0.3 to 0.5 mm/s/orbit, the Mars 2020 EDL phasing campaign is expected to be challenging requiring at least three planned OSMs as the timing uncertainties are anticipated to be large.[1]

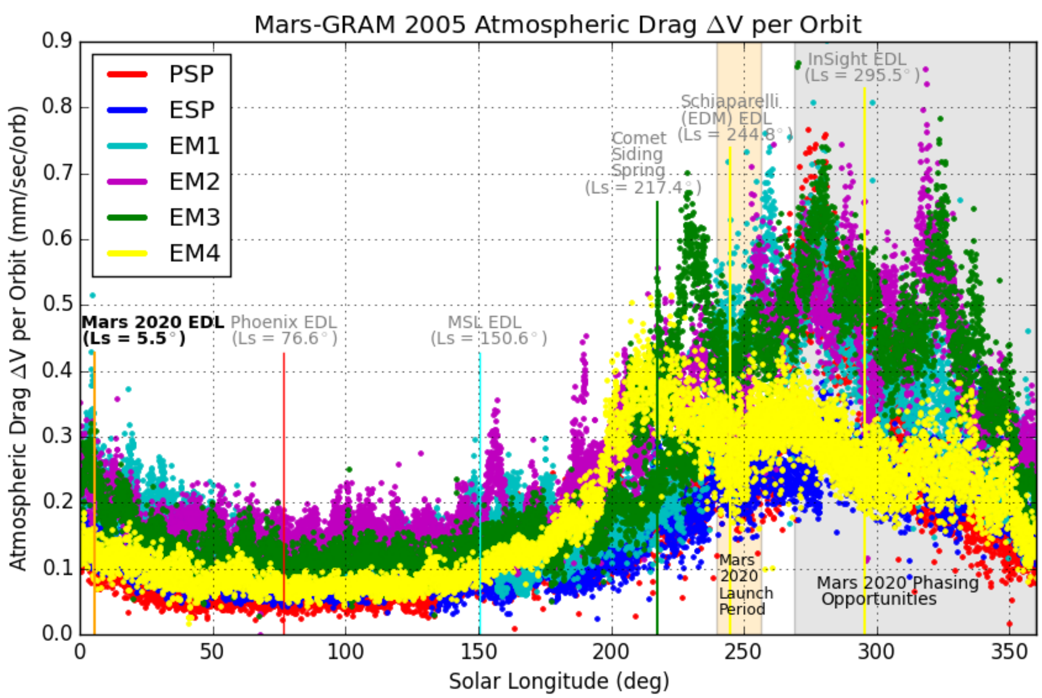


Figure 4: Atmospheric Drag ΔV Experienced by MRO through December 2018. *Color-coded by mission phase: PSP = Primary Science Phase, ESP = Extended Science Phase, EM = Extended Mission (1-4).*

MRO SCIENCE OPERATIONS FOLLOWING MARS 2020 EDL SUPPORT

The current plan as outlined in the 20181115 Reference Trajectory (see previous section) is to maintain the 3:15 PM LMST orbit that will be established for Mars 2020 EDL support in February 2021. Several considerations were made in the designs of the OCMs used to achieve this reference trajectory. During solar conjunction, the Sun-Earth-Probe (SEP) angle becomes significantly small resulting in very noisy tracking data. Maneuvers are generally scheduled well ahead of or after a solar conjunction period. For the 20181115 Reference Trajectory, OCM-6 was placed after the solar conjunction period in November 2023 and OCM-7 was modeled just before the solar conjunction period in March 2028. The LTST operational constraint for MRO to remain between 2:00 PM and 4:00 PM was also considered in the OCM designs. OCM-4 was not only performed soon after InSight EDL to reduce the ΔV expenditure but to also keep the local minimum LTST in January 2019 later than 2 PM. OCMs 5 and 6 were targeted to slightly under 3:15 PM LMST to ensure the maximum LTSTs in January 2024 and November 2027, respectively, remained just earlier than 4 PM. Although this reference trajectory maintains the LMST near 3:15 PM which is at the upper bound of the PSO requirement (3 PM $\pm$ 15 minutes), it meets the requirement for the LTST to remain between 2 PM and 4 PM. Note that this current plan does not preclude moving to a later LMST at a future date if needed. A summary of the significant events for MRO following InSight EDL such as the OCM dates, solar conjunction periods, and the dates of the minimum and maximum LTSTs which are near operating limits are given in Table 3.

Table 3: Significant Events Through 2028

Event	Date(s)
InSight EDL	November 26, 2018
OCM-4 (OTM-52)	December 12, 2018
Minimum LTST ($\sim$2:00:30 PM)	January 20, 2019
Solar Conjunction (SEP angle $< 3°$)	August 25–September 10, 2019
Mars 2020 Launch Period (Baseline)	July 17–August 5, 2020
Mars 2020 Launch Period (Extended)	August 6–12, 2020
Mars 2020 Phasing Opportunities	September 2020–February 2021
Mars 2020 EDL	February 18, 2021
OCM-5	April 14, 2021
Solar Conjunction (SEP angle $< 3°$)	September 29–October 17, 2021
Solar Conjunction (SEP angle $< 3°$)	November 8–28, 2023
Maximum LTST ($\sim$3:59:00 PM)	January 27, 2024
OCM-6	March 27, 2024
Solar Conjunction (SEP angle $< 3°$)	December 29, 2025–January 21, 2026
Maximum LTST ($\sim$3:59:30 PM)	November 1, 2027
OCM-7	December 15, 2027
Solar Conjunction (SEP angle $< 3°$)	March 7–April 3, 2028

Sun Eclipse Durations

Figure 9 displays the Sun eclipse durations as a function of solar longitude (L_s) through the end of the reference trajectory, representing approximately five Mars years. Following OCM-5 in April 2021, the LMST is maintained near 3:15 PM. The maximum eclipse durations range between $\sim$25 min and $\sim$40 min during the reference trajectory span. See Appendix C for the maximum eclipse durations that were expected with the previous plan to move to 4:30 PM LMST for battery management.

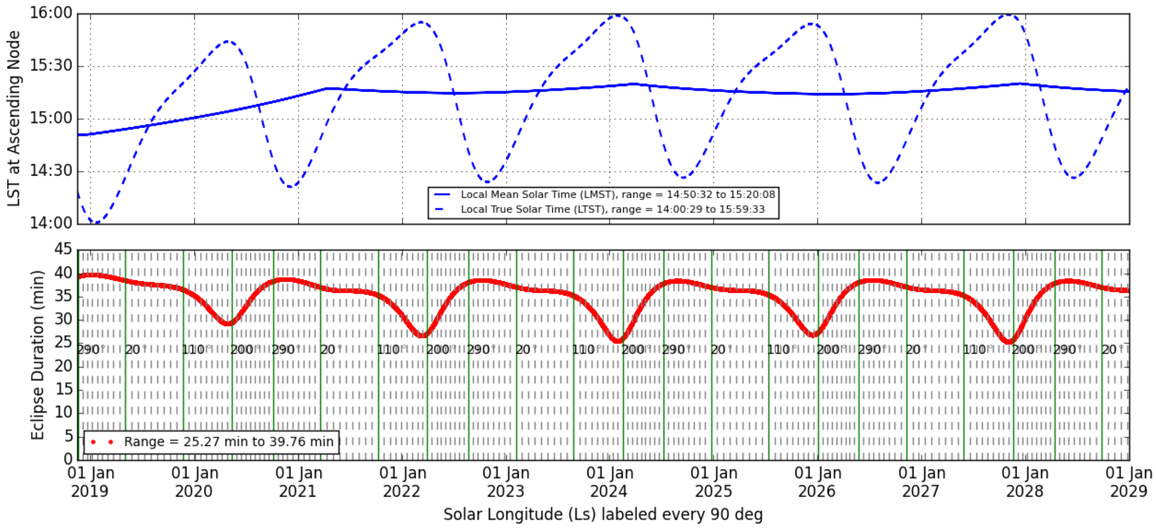


Figure 5: Sun Eclipse Durations with Orbit Maintained at 3:15 PM LMST After Mars 2020 EDL

CONCLUSION

The MRO Navigation Team has successfully supported science operations and relay for landed missions at Mars for nearly 12 years through the implementation of more than 50 propulsive maneuvers. MRO maneuvers were successful in controlling the GTW errors within mission requirements while maintaining the frozen condition of the science orbit. MRO also implemented maneuvers that satisfied LMST requirements for the PSO as well as the EDL sequences of incoming missions such as InSight on November 26, 2018. As of December 2018, MRO has a sizeable margin of about 194 kg of usable fuel, which translates to nearly 400 m/s of remaining ΔV. The current maneuver plan to support Mars 2020 EDL in February 2021 and maintain MRO's orbit near 3:15 PM LMST for science operations thereafter has a deterministic cost of about 10 m/s, a small percentage of this available ΔV. This plan, however, does not preclude increasing the LMST further if needed at a later date. The first part of the maneuver plan was implemented with the nominal execution of OTM-52 on December 12, 2018. The Mars Exploration Program Office expects MRO to continue providing relay support through 2028. The proposed plan presented in this paper will help ensure this expectation is met while preserving MRO's primary science operations at Mars.

ACKNOWLEDGMENTS

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APPENDIX A: MANEUVER PERFORMANCE

The maneuvers performed since March 2017 are summarized in Table 4 (previous maneuvers performed since science operations began in November 2006 are summarized in Reference 10). For each maneuver, the table lists the burn time, burn location in the orbit (apsis or equator crossing), the GTW error target if specified, and the predicted and reconstructed maneuver parameters. These parameters include the magnitude, right ascension, and declination of the burn ΔV. Depending on the maneuver size, the Spacecraft Team at Lockheed Martin used either a 25% or 75% duty cycle for MRO burns, the latter of which was utilized for all inclination-change maneuvers performed. Also, the minimum maneuver capability of 20 mm/s in ΔV magnitude was considered when designing these maneuvers.

Table 4: MRO Maneuver History (2017–2018)

<table>
<tr><th rowspan="2">Maneuver</th><th rowspan="2">Maneuver Epoch (UTC SCET)</th><th rowspan="2">Apsis or Node</th><th rowspan="2">GTW Tgt. (km)</th><th colspan="2">ΔV Magnitude (m/s)</th><th colspan="2">ΔV Right Ascension (deg)</th><th colspan="2">ΔV Declination (deg)</th><th rowspan="2">Comments</th></tr>
<tr><th>Pred.</th><th>Rec.</th><th>Pred.</th><th>Rec.</th><th>Pred.</th><th>Rec.</th></tr>
<tr><td rowspan="2">OTM-48 (OCM-3)</td><td rowspan="2">22-Mar-2017 13:38:40</td><td rowspan="2">DEqX</td><td rowspan="2">−60</td><td>3.1967</td><td>3.2033</td><td>191.37</td><td>191.02</td><td>12.49</td><td>13.11</td><td rowspan="2">Achieve 2:52 PM LMST @ InSight EDL in Nov. 2018</td></tr>
<tr><td colspan="6">3.17 m/s out-of-plane, 0.412 m/s in-plane</td></tr>
<tr><td>OTM-49</td><td>13-Sep-2017 13:34:55</td><td>Apo</td><td>−40</td><td>0.2160</td><td>0.2177</td><td>197.55</td><td>197.52</td><td>19.78</td><td>19.74</td><td></td></tr>
<tr><td>OTM-50 (OSM-1)</td><td>22-Aug-2018 12:25:50</td><td>Peri</td><td></td><td>0.3384</td><td>0.3438</td><td>196.48</td><td>196.27</td><td>19.09</td><td>19.01</td><td>InSight EDL phasing pro-velocity maneuver</td></tr>
<tr><td>OTM-51 (OSM-2)</td><td>24-Oct-2018 13:01:46</td><td>Peri</td><td></td><td>0.0568</td><td>0.0586</td><td>226.01</td><td>225.65</td><td>2.96</td><td>3.19</td><td>InSight EDL phasing pro-velocity maneuver</td></tr>
<tr><td rowspan="2">OTM-52 (OCM-4)</td><td rowspan="2">12-Dec-2018 14:18:23</td><td rowspan="2">DEqX</td><td rowspan="2">−60</td><td>1.4030</td><td></td><td>1.23</td><td></td><td>−60.50</td><td></td><td rowspan="2">Achieve 3:15 PM LMST @ Mars 2020 EDL in Feb. 2021</td></tr>
<tr><td colspan="6">1.2 m/s out-of-plane, 0.727 m/s in-plane</td></tr>
</table>

A Gates model[11] is used to represent execution errors for MRO propulsive maneuvers. For the 3σ magnitude error model, the fixed error is 5 mm/sec for small maneuvers (typically under 1 m/s) and 0.02 m/s for large maneuvers, and the proportional error is 2% of the maneuver magnitude. Beginning with the PSP mission, the 3σ fixed-pointing error is 0.02 m/s and the proportional-pointing error is 2% of the maneuver magnitude. Small in-plane maneuvers for orbit phasing are primarily impacted by down-track timing errors (i.e., magnitude errors). Maneuver magnitude errors have been typically less than 2% of the desired maneuver magnitudes, as seen in Figure 6. The Y-axis shows the percentage of difference in ΔV magnitude. Also highlighted with blue circles are the six inclination-change maneuvers (OTM-12, OTM-39, OTM-43, OTM-44, OTM-48, and OTM-52). Most of the maneuvers have had slight over-performances, indicated by a positive percentage in the figure.

The pointing errors of large out-of-plane maneuvers used for LMST control can affect the desired inclination change. For example, the $\sim$2% right ascension error in OTM-44 decreased the desired LMST drift. This caused the minimum LTST in early March 2017 to be lowered from 2:02 PM to 2:01:30 PM and delayed the 3:00 PM LMST crossing point from September 2017 to October 2017. These pointing errors also introduce down-track magnitude errors which can have a non-trivial impact on the GTW error maintenance.

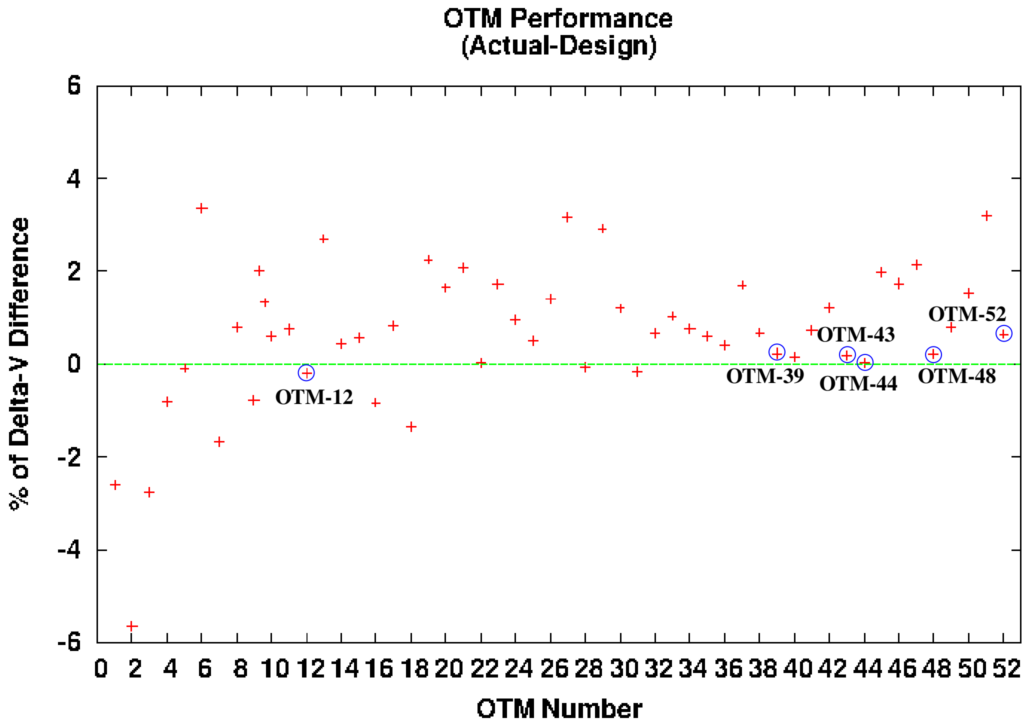

Figure 6: Performance of OTMs 1–52 (February 2007 – December 2018)

APPENDIX B: PSO MAINTENANCE

GTW Error Maintenance

Figure 7 shows the maintenance of the 211-orbit GTW repeat error since January 2017 through December 2018. OTM-49 was primarily performed to control the GTW error by targeting -40 km. OTMs 48 and 52 were executed to change the nodal drift for InSight and Mars 2020 EDL support, respectively, but also contained pro-velocity in-plane components to help control the GTW error. OTMs 50 and 51 were designed for InSight EDL phasing but also aided in the GTW error control by being in the pro-velocity direction (see Reference 1).

Frozen Condition Maintenance

One of the PSO requirements is to keep periapsis about the Mars South Pole frozen. This is usually accomplished via the execution of in-plane GTW maintenance maneuvers. The mean eccentricity vs. mean argument of periapsis ($e - \omega$) space is used to track this frozen orbit condition. There was no hard requirement on how tight the e-ω curve should be, but just to keep the orbit frozen. The MRO Navigation Team currently contains the e-ω variation such that ω varies within 3 deg about 270 deg. In comparison, Mars Global Surveyor had kept e-ω between 263° and 277°(at apoapsis); Mars Odyssey has been within 262° and 278° (at apoapsis). The entire mean e-ω reconstructed history from the beginning of science operations in November 2006 through just prior to the execution of the most recent maneuver performed in December 2018 (OTM-52) is shown in Figure 8. Highlighted in the figure is the affect of performing OTM-52 (OCM-4) at the descending equator crossing. If OTM-52 was performed at the ascending equator crossing, the arrow shown in the figure would have moved instead to the right by the same amount, placing the mean argument of periapsis of the MRO frozen condition outside of 274° into new territory.

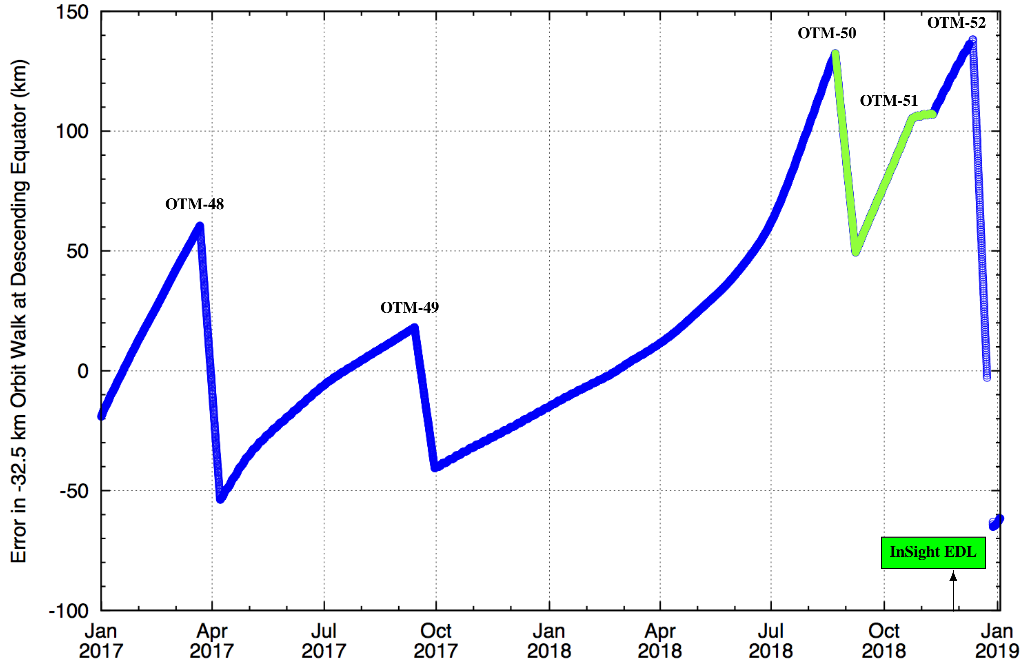

Figure 7: MRO Orbit Ground Track Walk Repeat Error from January 2017 – December 2018. *GTW control (blue), pro-velocity phasing for InSight EDL (green).*

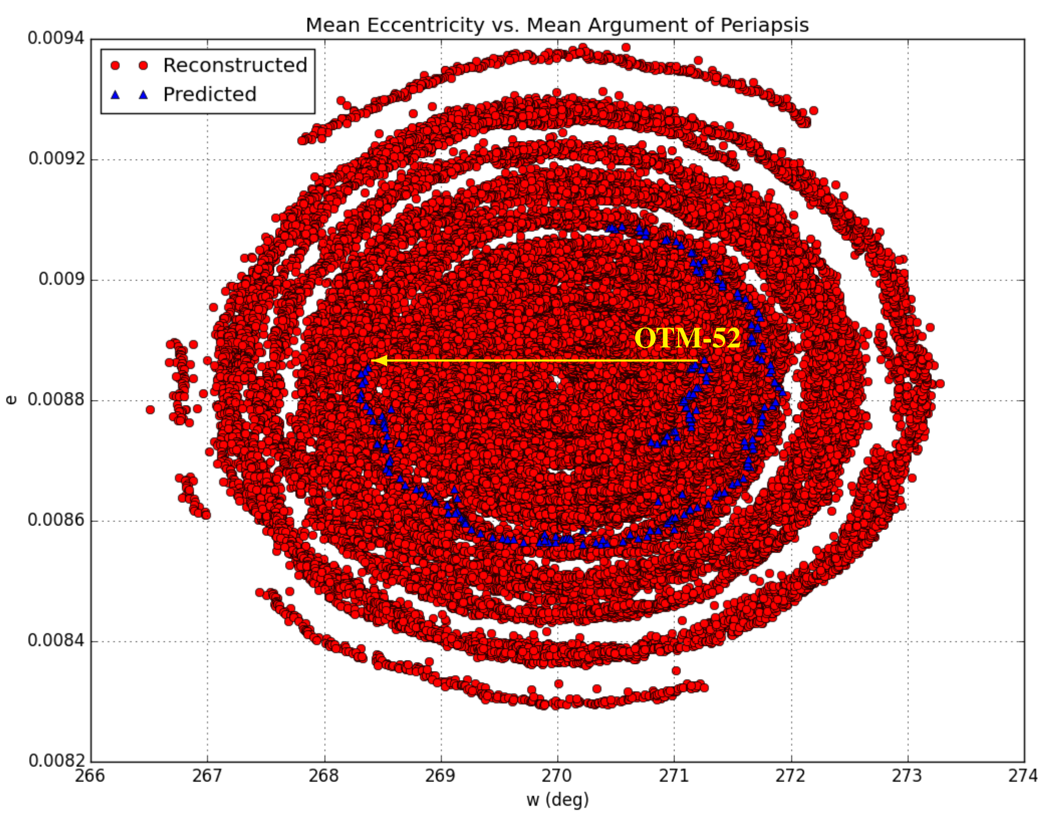

Figure 8: Reconstructed Mean $e - w$ (Frozen about Mars South Pole) from 2007-2018

APPENDIX C: PREVIOUS PLAN TO MAINTAIN ORBIT AT 4:30 PM LMST AFTER MARS 2020 EDL SUPPORT

Described below is the previous 20180305 Reference Trajectory[2] for supporting Mars 2020 EDL at 3:30 PM LMST and then establishing a 4:30 PM LMST for battery management. The total required maneuver ΔV for this reference trajectory is 41.74 m/s, accomplished via OCMs 4–7 (see Table 5). Atmospheric drag was not modeled and burns were centered at the ascending equator crossings. The ΔV and estimated propellant usage for each maneuver can be found in Table 5, as well as the inclination change and the LMST at the time of each maneuver. In this reference trajectory, OCM-4 is modeled on December 12, 2018 to change the nodal drift such that 3:30 PM LMST is achieved for Mars 2020 EDL on February 18, 2021. Two months after Mars 2020 EDL, OCM-5 increases the LMST drift such that 4:30 PM is achieved seven months later. OCM-6 on November 10, 2021 then arrests the LMST drift at 4:30 PM. Finally, OCM-7 is modeled on December 11, 2024 for LMST maintenance between 4:30 PM and 4:40 PM.

Table 5: OCM Strategy to Maintain Orbit at 4:30 PM LMST After Mars 2020 EDL

Maneuver	Maneuver Epoch (UTC-SCET)	ΔV (m/s)	Prop. Usage (kg)	Inc. Change (deg)	LMST	Comments
OCM-4	12-Dec-2018 12:49:59	2.78	1.51	0.048	2:50:38 PM	3:30 PM LMST for Mars 2020 EDL
OCM-5	14-Apr-2021 13:32:23	15.70	8.52	0.263	3:35:20 PM	Achieve 4:30 PM LMST by Nov. 2021
OCM-6	10-Nov-2021 13:47:07	20.50	11.12	−0.344	4:30:06 PM	Arrest drift at 4:30 PM LMST
OCM-7	11-Dec-2024 14:39:21	2.76	1.50	−0.047	4:40:06 PM	Return to 4:30 PM LMST by Dec. 2027
	Total	**41.74**	**22.65**			

Figure 9 displays the Sun eclipse durations as a function of solar longitude (L_s) through the end of the 20180305 Reference Trajectory, representing approximately five Mars years. Following OCM-6 in November 2021, the LMST was to be maintained at 4:30 PM. Starting in 2022 it can be seen that eclipses no longer occur at solar longitudes near 180° and that the maximum eclipse durations reduced from ∼40 min (current PSO orbit) to ∼31 min.

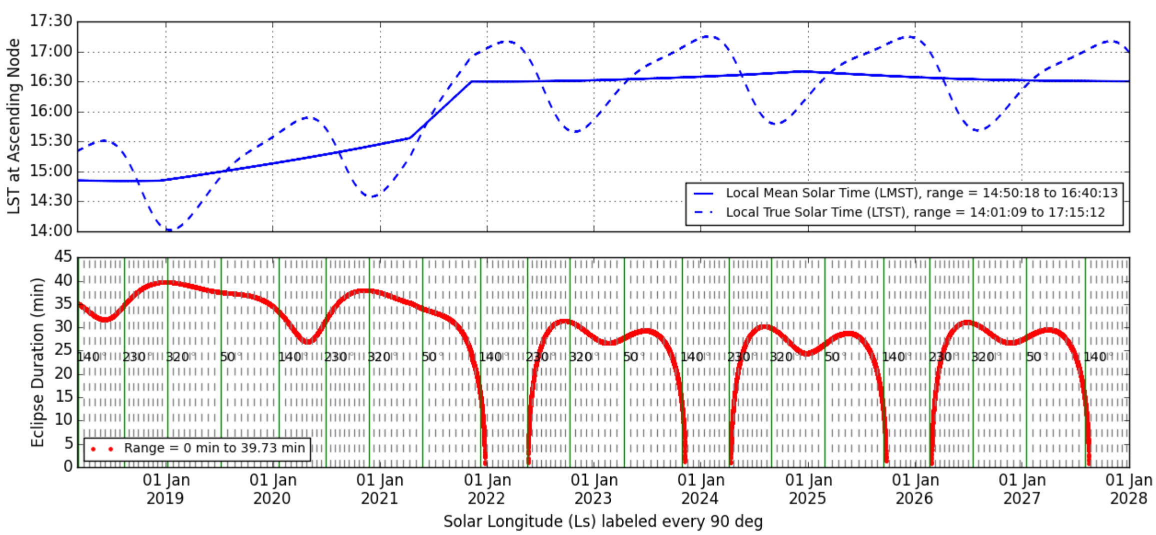

Figure 9: Sun Eclipse Durations with Orbit Maintained at 4:30 PM LMST After Mars 2020 EDL

REFERENCES

[1] P. R. Menon, S. V. Wagner, D. C. Jefferson, E. J. Graat, K. J. Lee, W. B. Schulze, R. M. Woollands, and K. E. Criddle, "Mars Reconnaissance Orbiter Navigation Strategy for Support of InSight Lander's Entry, Descent and Landing Sequence," *AAS/AIAA Space Flight Mechanics Meeting,* AAS 19-209, January 13–17, 2019.

[2] S. V. Wagner, "MRO 20180305 Reference Trajectory for InSight and Mars 2020 EDL Support and Battery Management at 4:30 PM LMST," JPL IOM 392C-18-002, April 18, 2018.

[3] S. V. Wagner, "MRO 20181115 Reference Trajectory for Mars 2020 EDL Support at 3:15 PM LMST," JPL IOM 392C-18-005, December 11, 2018.

[4] "Mars Reconnaissance Orbiter Navigation Plan," Tech. Rep. MRO-31-202, JPL D-22240, NASA Jet Propulsion Laboratory, Pasadena, CA, June 15, 2005.

[5] C. Edwards, K. Bruvold, J. Erickson, R. Gladden, J. Guinn, P. Ilott, B. Jai, M. Johnston, R. Kornfeld, T. Martin-Mur, G. McSmith, R. Thomas, P. Varghese, G. Signori, and P. Schmitz, "Telecommunications Relay Support of the Mars Phoenix Lander Mission," *Aerospace Conference, 2010 IEEE*, March 6–13, 2010.

[6] J. L. Williams, P. R. Menon, and S. W. Demcak, "Mars Reconnaissance Orbiter Navigation Strategy for Mars Science Laboratory Entry, Descent and Landing Telecommunication Relay Support," *AIAA/AAS Astrodynamics Specialist Conference,* AIAA 2012-4747, Minneapolis, Minnesota, August 13–16, 2012.

[7] P. R. Menon, S. V. Wagner, D. C. Jefferson, E. J. Graat, K. J. Lee, and W. B. Schulze, "Mars Reconnaissance Orbiter Navigation Strategy for the ExoMars Entry, Descent, and Landing Demonstrator Module (EDM) Mission," *AAS/AIAA Space Flight Mechanics Meeting,* AAS 17-337, San Antonio, TX, February 5–9, 2017.

[8] P. R. Menon, S. V. Wagner, T. J. Martin-Mur, D. C. Jefferson, S. M. Ardalan, M.-K. J. Chung, K. J. Lee, and W. B. Schulze, "Mars Reconnaissance Orbiter Navigation Strategy for the Comet Siding Spring Encounter," *AAS/AIAA Astrodynamics Specialist Conference,* AAS 15-551, Vail, Colorado, August 9–13, 2015.

[9] "Mars 2020 Project Navigation Plan, Revision-B," Tech. Rep. JPL D-95510, NASA Jet Propulsion Laboratory, Pasadena, CA, January 2019.

[10] S. V. Wagner, P. R. Menon, and S. W. Demcak, "Mars Reconnaissance Orbiter: Ten Years of Maneuver Support For Science Operations and Entry, Descent, and Landing Sequences," *AAS/AIAA Space Flight Mechanics Meeting,* AAS 17-287, San Antonio, TX, February 5–9, 2017.

[11] C. R. Gates, "A Simplified Model of Midcourse Maneuver Execution Errors," Tech. Rep. 32-504, NASA Jet Propulsion Laboratory, Pasadena, CA, October 15, 1963.